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Development of Canopy Reflectance Algorithms for Real-Time Prediction of Bermudagrass Pasture Biomass and Nutritive Values

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ABSTRACT

Timely assessments of forage biomass production and nutritive values during the growing season are important for livestock managers to make decisions for adjusting stocking rate and pasture management. Remote sensing of canopy reflectance may provide a rapid and inexpensive means of estimating pasture nutritive values and biomass. The objective of this study was to determine the relationships between neutral detergent fiber (NDF), acid detergent fiber (ADF), crude protein (CP) concentration, biomass, and CP availability of bermudagrass [*Cynodon dactylon* (L.) Pers.] pastures and canopy reflectance. An experiment was conducted in the 2002 and 2003 growing seasons using three bermudagrass pastures of 'Midland', 'Ozarka', and an experimental hybrid, 72x12–12. Pasture CP concentration, biomass and CP availability correlated linearly with the reflectance ratios of R_{605}/R_{515}, R_{915}/R_{975}, and R_{875}/R_{725} ($0.44 \leq r^2 \leq 0.63$) as well as with the first derivatives of reflectance with wavebands centered at 545, 935, and 755 nm ($0.49 \leq r^2 \leq 0.68$). Linear equations between each forage variable and the ratios or derivatives of reflectance were developed on the basis of data pooled across years, plant genotypes, and sampling dates. Validation of developed equations indicated that the CP concentration, biomass, and CP availability could be predicted by either the ratios or derivatives of the reflectance. Pasture NDF and ADF had lower correlation with canopy reflectance than other measured variables. Our results suggest that two-narrow-waveband reflectance ratios or the first derivatives in visible and near-infrared spectral regions can be used for real-time and nondestructive prediction of forage productivity and CP content in bermudagrass pastures.

Laboratory chemical analysis methods have long been used for assessments of forage nutritive quality (Kellems and Church, 1998). Major forage nutritive quality variables include neutral detergent fiber (NDF), acid detergent fiber (ADF), and crude protein (CP) concentrations. Laboratory chemical methods used to determine these quality variables are time consuming and costly and generate hazardous waste that must be disposed. Beginning in the mid 1970s, near-infrared reflectance spectroscopy (NIRS) was evaluated and used for determination of forage quality (Norris et al., 1976). Relative to chemical procedures, the NIRS analysis provides rapid and low-cost estimation of forage nutrient composition (Marten et al., 1989; Shenk and Westerhaus, 1994) and has been widely used for forage quality analysis. Although the NIRS has great advantages compared with the laboratory chemical method, it is still time consuming because it requires collection and processing (drying and grinding) of vegetation samples.

Potentially, remote sensing of pasture canopy reflectance could further reduce laborious field sampling and sample processing procedures and improve the efficiency of forage productivity and quality evaluation. Furthermore, it would permit mapping of the pasture nutritional landscape and provide timely information to ranch and livestock managers. Numerous studies have reported that remotely sensed data at leaf, canopy, or landscape level can be used to monitor plant growth, physiological, and biochemical properties (Chappelle et al., 1992; Curran et al., 1992; Peñuelas and Filella, 1998; Daughtry et al., 2000; Peñuelas and Inoue, 2000; Zhao et al., 2005a, 2005b), nutrient status and environmental stresses (Gausman, 1982; Chappelle et al., 1992; Filella et al., 1995; Ma et al., 1996; Blackmer et al., 1996; Voullot et al., 1998; Wang et al., 1998; Carter and Estep, 2002; Zhao et al., 2005a), and yields (Ma et al., 1996; Plant et al., 2000; Reddy et al., 2003) in field crops, but similar studies on estimation of forage quality variables using remote sensing are limited.

Because plant canopy reflectances in the visible (400–700 nm) and NIR (700–900 nm) wavelengths are primarily influenced by chlorophyll and leaf cell structure, respectively (Campbell, 1996; Peñuelas and Filella, 1998), changes in forage CP, NDF, and ADF would be expected to affect canopy reflectance in given wavebands in visible-NIR region. Richardson et al. (1983) used a hand-held radiometer to determine relationships between canopy reflectance values in the red to near infrared range and biomass and N content of Alicia bermudagrass. They concluded that remote sensing could be useful for rangeland management. Everitt et al. (1985) investigated relationships between leaf reflectance and leaf nitrogen or chlorophyll concentration in buffelgrass and concluded that leaf reflectance at 500 and 550 nm highly correlated with leaf N and chlorophyll concentrations. More recently, Lamb et al. (2002) reported that leaf reflectance in red-edge range of wavelengths (690–740 nm) could be used to estimate leaf N concentration and total N content of ryegrass (*Lolium multiflorum* Lam.). On the basis of the principles of bench-top near-infrared spectroscopy, Starks et al. (2004) analyzed the relationships between canopy reflectance in 252 wavebands, covering the 368- to 1100-nm region, and forage quality variables (i.e., NDF, ADF, and N concentrations) of bermudagrass pasture using modified partial least square regression methods. They found that forage N, NDF, and ADF concentrations closely and linearly correlated with pasture canopy reflectance.

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Abbreviations: ADF, acid detergent fiber; CP, crude protein; NDF, neutral detergent fiber.

Although the forage quality variables could be estimated from hyperspectral remotely sensed data by integrating canopy reflectance in all wavebands (Starks et al., 2004), it is not practical for livestock managers to predict forage nutritive variables using an expensive, full range hyperspectral radiometer. Starks et al. (2005) investigated the correlation of forage NDF, ADF, and CP with pasture canopy reflectance and reflectance ratios in broad wavebands (i.e., green, red, near-infrared, and shortwave infrared regions). They concluded that although the correlation coefficients (r) were statistically significant for most measured forage quality variables in all the broad wavebands, using both the broad wave-band canopy reflectance and reflectance ratios could only explain a small portion of variance in the forage quality variables.

Studies have shown that in various species, leaf N and chlorophyll concentration are related to the leaf hyperspectral reflectance ratios (Carter and Spiering, 2002; Read et al., 2002; Zhao et al., 2005a) and first derivatives of reflectance (Lamb et al., 2002; Zhao et al., 2005b). In this study, we hypothesized that some remote sensing indices may be used to rapidly estimate NDF, ADF, CP, and aboveground biomass of pastures over the growing season. The objectives were to (i) determine the relationships between forage biomass and nutritive values and canopy reflectance in both narrow and broad wavebands and (ii) develop and validate reflectance algorithms on the basis of a few narrow wavebands for real-time prediction of pasture nutritive values and biomass production.

MATERIALS AND METHODS

Experimental Location

A field experiment was conducted at the USDA-ARS Grazinglands Research Laboratory, El Reno, OK (Lat. 35°32′ N, Long. 98°02′ W) in the 2002 and 2003 growing seasons. Three perennial warm-season bermudagrass pastures of Midland, Ozarka, and 74x12–12 were selected for collection of biomass, forage quality, and remotely sensed data at canopy level. The three pastures were established in 1991 with similar field size (3.2 ha), soil type [Brewer silt clay loam (fine-loamy, mixed, thermic Udic Rhodustalfs)], production management, and stocking rate (3 steers ha^{-1}). Fertilizer applications were based on soil test results and production recommendations for bermudagrass production with a urea N fertilizer rate of 77 kg N ha^{-1} in 2002 and 67 kg N ha^{-1} in 2003 at the start of the growing season (late April to early May). Each field was split into eight plots for sampling. The plot size was about 0.4 ha.

Measurements

In early, mid-, and late growing season of 2002 and biweekly throughout the growing season of 2003, canopy hyperspectral reflectance measurements were made during clear days between 1000 and 1200 h (Central Standard Time) from all plots of each genotype. A portable ASD FieldSpec FR spectroradiometer[1] (Analytical Spectral Devices Inc., Boulder, CO) was used to collect the canopy reflectance data. The ASD measures spectral reflectance in the 350- to 2500-nm wavelength range with a 1-nm sampling interval. The optical sensor of the spectroradiometer was mounted on a boom 2 m above and perpendicular to the soil surface. The radiometer had a 25° field-of-view, producing a view area with a 0.89-m diameter. A Spectralon (Labsphere, Inc., Sutton, NH) reference panel (white reference) was used to optimize the ASD instrument before taking three canopy reflectance measurements at each sampling plot. The canopy reflectance data were expressed as relative values by dividing them by the white reference panel reflectance readings.

All pasture vegetation in a 0.25-m^2 area within the ASD field of view was clipped within 1 cm of the ground surface after canopy reflectance measurements. Pasture samples were immediately dried, weighed, and ground for determinations of NDF and ADF concentrations according to standard laboratory procedures of forage quality analysis outlined by Ankom Technology (Fairport, NY) (http://www.ankom.com/09_procedures/procedures.shtml; verified 29 November 2005). Total N concentration in dry materials was determined using an automated combustion instrument (LECO Corp., St. Joseph, MI).

Data Analysis

Forage CP concentration was calculated by multiplying N concentration by 6.25 (Pearson and Ison, 1987). The CP availability (kg ha^{-1}) was estimated by multiplying biomass by plant CP concentration. Pasture biomass and quality variables were pooled over plant genotypes, sampling dates and plots within a year. The maximum, minimum, mean, standard deviation (SD), and coefficients of variation (CV) for each forage variable were calculated.

The spectral reflectance values measured from the three adjacent points in each plot at each sampling date were first averaged. Canopy reflectance data in the four-wavelength ranges of 350 to 399, 1350 to 1449, 1700 to 1969, and 2300 to 2500 nm were first omitted from the reflectance data sets because of instrument noise or location of these bands within regions of atmospheric moisture absorption. The remaining reflectance data were combined into six broad wavebands: blue (450–520 nm), green (520–600 nm), red (630–690 nm), NIR (760–900 nm), short-wave infrared 1 (SWIR1, 1550–1750 nm), and short-wave infrared 2 (SWIR2, 2080–2300 nm), on the basis of the Thematic Mapper (TM) bands. The measured forage biomass and quality variables and corresponding reflectance data were pooled across years, genotypes, plots, and sampling dates (n = 144). Coefficients of determination (r^2) between the forage variables and canopy reflectance values in each broad waveband were calculated.

In addition to reflectances in broad wavebands, reflectances in narrow wavebands were calculated by averaging over 10-nm intervals between 400 and 2300 nm and a total of 153 narrow wavebands were produced. Both measured forage quality variables and the narrow waveband reflectance data were pooled as described above. Relationships between the pasture biomass and nutritive values and canopy reflectance values at different narrow wavebands (10 nm) were determined to develop reflectance algorithms for estimating the forage biomass and measured nutritive values. The pooled data were randomly assigned into calibration and test sets to develop and validate algorithms between the measured forage variables and narrow-band canopy reflectance measurements. Each data set contained 72 samples.

Several different methods to transform the narrow waveband reflectance data were used to find the best functional relationships between measured forage variables and canopy remotely sensed measurements. In addition to simple reflectance (R), four additional reflectance datasets were derived:

[1] Use of trade or product names is for informational purpose only and dose not imply endorsement by the United State Department of Agriculture to the exclusion of any other product that may be suitable.

(i) reflectance ratios; (ii) log (1/*R*); (iii) first derivatives of *R*; and (iv) first derivatives of log (1/*R*). The log (1/*R*) and the first derivatives of *R* or log (1/*R*) were calculated according to Hruschka (1987) and Lamb et al. (2002), respectively.

The linear regression analyses of forage biomass and quality variables with all of corresponding untransformed and transformed narrow-band reflectance data throughout the wavelength range of 400 to 2300 nm in the calibration data set were performed. The log (1/*R*) and the first derivatives of log (1/*R*) transformations did not improve the linear relationships between the forage nutritive values and canopy reflectance compared with the original reflectance and the first derivatives of reflectance. Therefore, these two data sets did not undergo further analysis. The wavebands where reflectance values had the greatest r^2 with NDF, ADF, CP, biomass, and CP availability were first selected. The reflectance values at these particular wavebands were used as the numerators and reflectance values at all other wavebands were used as denominators to calculate reflectance ratios according to Zhao et al. (2005a). The r^2 values of all the forage quality variables with the reflectance ratios or with the first derivatives of reflectance were further determined.

The reflectance ratios and first derivatives of reflectance in the calibration data set, having the greatest r^2 values with forage quality variables, were selected. Concentrations of NDF, ADF, and CP, total biomass and CP availability from the calibration data set were then plotted against the corresponding reflectance ratios or the first derivatives of reflectance, and linear regressions were performed for each quality variable. Additionally, each measured forage quality parameter was treated as a response variable in a stepwise regression (SAS, 1997) to determine relationships between the NDF, ADF, CP, biomass, and CP availability and reflectance or first derivatives of the reflectance in five most important wavebands. These forage parameters in the test data set were predicted on the basis of the algorithms developed from the data in the calibration set and the reflectance values of the test set. Predicted NDF, ADF, CP, biomass, and CP availability were plotted against their laboratory-measured results to validate algorithm usefulness. The root-mean-square error (RMSE) was calculated to determine the precision of estimation between the measured values and predicted values.

RESULTS AND DISCUSSION

Biomass and Nutritive Values

Neutral detergent fiber ranged between 61.8 and 78.0%, ADF was between 28.1 and 41.3%, CP between 4.1 and 16.3%, biomass between 664 and 8968 kg ha^{-1}, and CP availability between 36 and 1125 kg ha^{-1} in the two growing seasons (Table 1). Overall, CP availability had the greatest (CV = 45–59%) and NDF had smallest (CV = 3.4–4.9%) variability among these forage variables. Changes in NDF and ADF in the present study were much smaller than changes in CP concentration, aboveground biomass, and CP availability. These results are consistent with findings in ungrazed forage fields, where the CV of forage yield and CP concentration were greater than the CV of NDF and ADF among bermudagrass genotypes, harvest dates, and years (Taliaferro et al., 1995, 2000). Wide ranges in forage CP concentration, biomass production, and CP availability provided the ideal data sets for development and validation of reflectance algorithms in these forage biomass and quality variables.

Table 1. Descriptive statistics of neutral detergent fiber (NDF), acid detergent fiber (ADF), crude protein (CP), aboveground biomass, and CP availability (CPA) of three bermudagrass (Midland, Ozarka, and 74x12–12) pastures across genotypes, sampling sites and measuring dates in 2002 and 2003.

Parameter	NDF	ADF	CP	Biomass	CPA
	percentage of biomass			kg ha^{-1}	
2002 (n = 52)					
Maximum	75.3	36.9	16.3	8968	1125
Minimum	61.8	28.7	4.8	1044	65
Mean	69.8	33.9	9.4	5164	507
SD	3.4	1.9	2.8	1903	230
CV (%)	4.9	5.7	30.3	37	45
2003 (n = 92)					
Maximum	78.0	41.3	13.4	7108	661
Minimum	67.2	28.1	4.1	664	39
Mean	73.4	33.6	7.4	3279	244
SD	2.5	2.6	2.1	1568	145
CV (%)	3.4	7.7	27.9	48	59

Correlation of Forage Quality Variables with Broadband Reflectance

Among the six broad wavebands, reflectances in red and NIR bands were most highly correlated with forage NDF, ADF, CP concentration, aboveground biomass, and CP availability (Fig. 1). Most r^2 values of these forage quality variables with canopy reflectance in a single broadband were statistically significant ($P < 0.05$–0.0001) because of a large data set ($n = 144$). However, using the reflectance in any broad waveband could only explain 4 to 21% of the variation in NDF, 1 to 15% in ADF, 4 to 34% in CP, 15 to 39% in biomass, and 16 to 52% in CP availability (i.e., small r^2 values). These results indicate that correlations of standing pasture

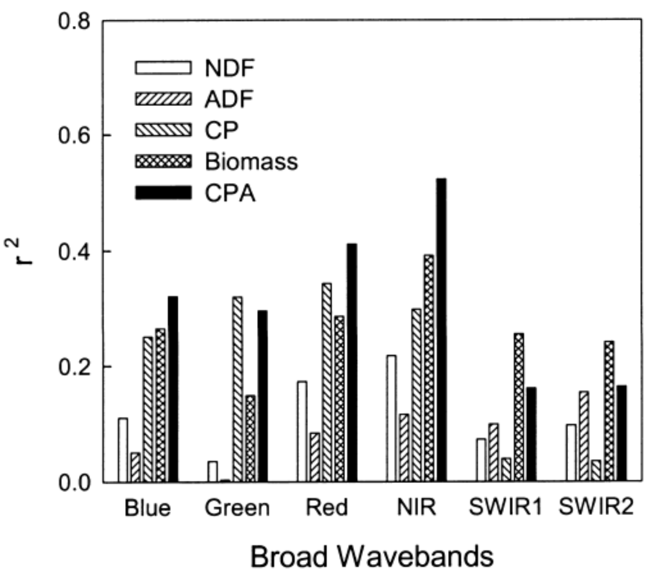

Fig. 1. Coefficients of determination (r^2) of forage neutral detergent fiber (NDF), acid detergent fiber (ADF), crude protein (CP) concentrations (%), aboveground biomass (Mg ha^{-1}), and CP availability (CPA, kg ha^{-1}) with canopy reflectances in broadwavebands of blue (450–520 nm), green (520–600 nm), red (630–690 nm), near infrared (NIR, 760–900 nm), short-wave infrared 1 (SWIR1, 1550–1750 nm), and short-wave infrared 2 (SWIR2, 2080–2350 nm) ($n = 144$).

canopy reflectance in single broad wavebands with measured forage biomass and quality variables of bermudagrass are low (Fig. 1). Therefore, narrow waveband reflectance and other data analysis methods were investigated to determine if relationships between pasture canopy reflectance and forage quality could be improved to more accurately predict forage productivity and nutritive values using remotely sensed data.

Relationships between Narrowband Reflectance and Forage Quality Variables

Linear regression analysis of each quality variable with canopy reflectance values at all narrow wavebands indicated that the r^2 between the quality parameters and the reflectance data depended on both measured quality variables and the wavebands (Fig. 2a). Overall, the r^2

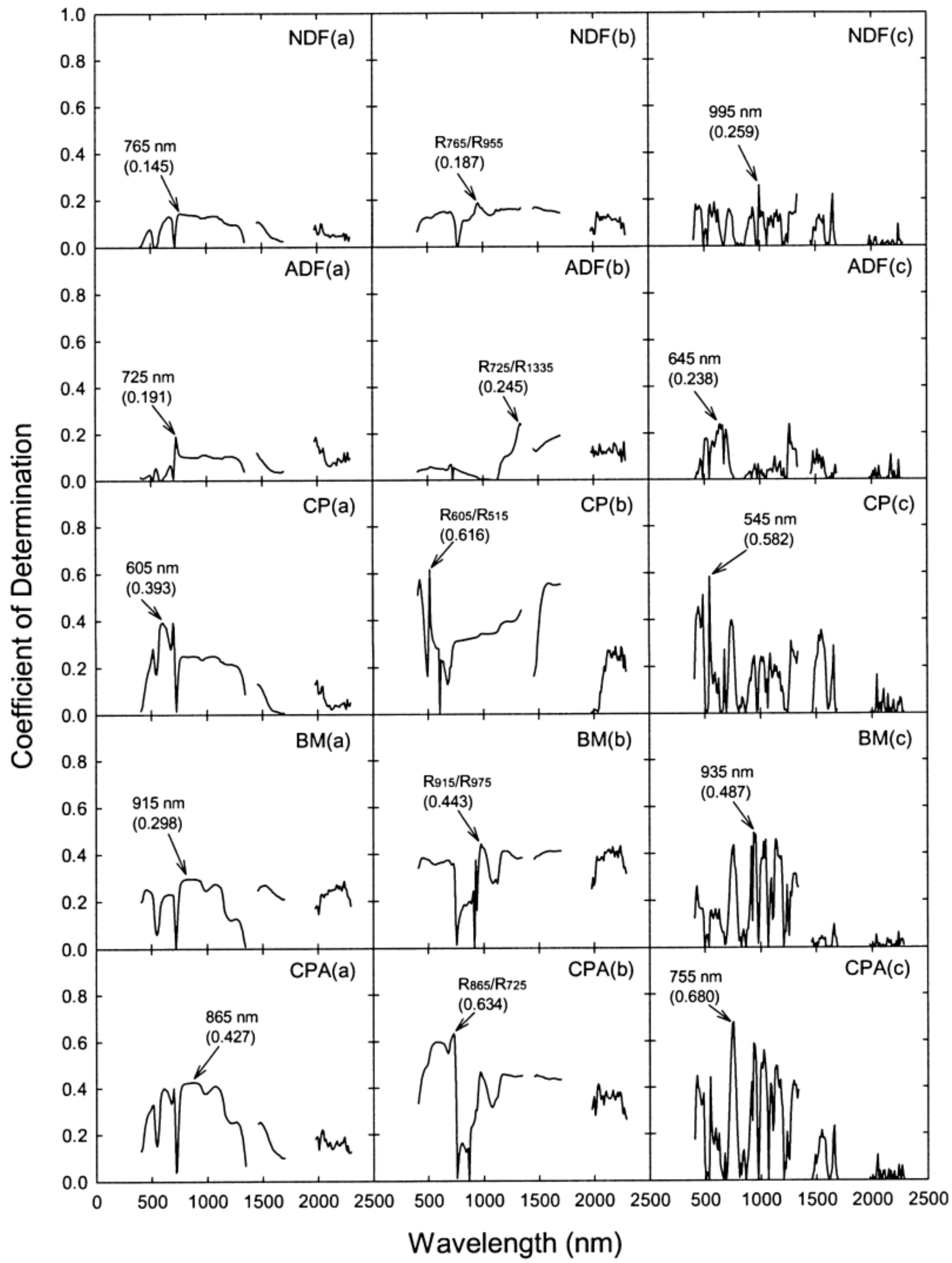

Fig. 2. Coefficients of determination (r^2) vs. wavelengths for the relationships of forage neutral detergent fiber (NDF), acid detergent fiber (ADF), crude protein (CP) concentrations (%), aboveground biomass (Mg ha^{-1}), and CP availability (CPA, kg ha^{-1}) with (a) canopy reflectance, (b) reflectance ratios, and (c) the first derivatives of reflectance at different wavelengths. The r^2 values were based on a linear model of the calibration data set. Typical wavebands where the reflectances, reflectance ratios or the first derivatives of reflectance have the greatest r^2 (in parenthesis) with the forage quality parameters are highlighted in the figure (n = 72).

values of NDF and ADF with reflectances were lower than those of CP, biomass, and CP availability in most wavebands. The reflectances centered at 765, 725, 605, 915, and 865 ± 5 nm (i.e., R_{765}, R_{725}, R_{605}, R_{915}, and R_{865}) had the greatest r^2 with NDF, ADF, CP, biomass, and CP availability, respectively (Fig. 2a). Although reflectance values in most wavebands were significantly correlated with these forage quality variables ($P < 0.05$), reflectance in a single narrow waveband having the greatest r^2 could only explain 15% of variation in NDF, 19% in ADF, 39% in CP, 30% in biomass, and 43% in CP availability (Fig. 2a).

Several studies on different plant species have indicated that two-waveband reflectance ratios of plant leaves correlated more closely with leaf chlorophyll and leaf N concentration, compared with leaf reflectance in a single narrow waveband (Carter and Spiering, 2002; Read et al., 2002; Zhao et al., 2005a, 2005b). First derivatives of reflectance in the red-edge region (690–740 nm) have been used to estimate leaf N concentration in ryegrass (Lamb et al., 2002) and in sorghum [*Sorghum bicolor* (L.) Moench](Zhao et al., 2005b). Similar to previous reports, both the reflectance ratios (Fig. 2b) and the first derivatives of reflectance (Fig. 2c) in most wavebands in the present study improved linear relationships between canopy reflectance and NDF, ADF, CP, biomass, and CP availability (i.e., greater r^2 values than the simple reflectance). The two-waveband reflectance ratios having the greatest r^2 with NDF, ADF, CP, biomass, and CP availability were R_{765}/R_{955}, R_{735}/R_{1335}, R_{605}/R_{515}, R_{915}/R_{975}, and R_{875}/R_{725}, respectively. Wavebands of the first derivatives of reflectance having the greatest r^2 with the five forage variables centered at 995, 645, 545, 935, and 755 nm, respectively (Fig. 2c).

It is noted that data were pooled across the three genotypes and used to determine the relationships between measured forage parameters and canopy reflectance measurements in the present study. This might cause lower r^2 values in linear regression analysis as compared with data assessment in an individual plant genotype. However, the primary objective of our study was to develop reflectance algorithms for real-time prediction of forage productivity and nutritive values of bermudagrass pastures across genotypes rather than one specific cultivar. Thus, the equations developed from the pooling data might be more useful compared with those based on a given grass genotype.

Scatter plots indicated that relationships between all measured forage quality variables and the given reflectance ratios or the first derivatives of reflectance with the greatest r^2 could be expressed in a linear fashion (graphs not shown). These linear equations and r^2 values, derived from the calibration data set, are given in Table 2. The particular reflectance ratios explained 19, 25, 62, 44, and 63% of the variance, respectively, in forage NDF, ADF, CP concentration, biomass, and CP availability. The first derivatives of reflectance in the selected wavebands explained 26, 24, 58, 49, and 68% of the variance, respectively, in these forage biomass and quality variables (Table 2). Generally, the correlations of NDF and ADF with the reflectance ratios or first derivatives of reflectance were much lower than those of CP concentration, biomass, and CP availability. An earlier study on a number of plant species suggested that tissue N or CP concentration in dry ground materials was most highly correlated with reflectance at wavelengths between 1200 and 2400 nm (Kokaly, 2001). However, in field settings canopy reflectance in the spectral range of 1200 to 2400 nm is greatly reduced by moisture in plant tissues and in the atmosphere. The close relationships between forage CP concentration and R_{605}/R_{515} or the first derivative of reflectance at 545 nm in the present study could avoid the influence of moisture on canopy reflectance.

The five most important wavebands for each measured forage quality variable and the corresponding multivariable equations and r^2 values, obtained by stepwise regression, are given in Table 3. Compared with the simple reflectance ratios and first derivatives of reflectance, the linear relationships between forage NDF, ADF, CP concentration, biomass, and CP availability and canopy reflectance were slightly improved by multiple regression of the five-waveband reflectances or first derivatives of reflectance (i.e., greater r^2, Table 3).

Algorithm Validation

Forage NDF, ADF, CP concentration, biomass, and CP availability in the test data set were predicted by the corresponding equations of the two-waveband reflec-

Table 2. The best wavebands (±5 nm) selected from reflectance (*R*) ratio calculation and from first derivatives of R (FDR) for determining their linear relationships with forage quality variables of neutral detergent fiber (NDF), acid detergent fiber (ADF), crude protein (CP) concentrations, aboveground biomass, and CP availability (CPA) on the basis of the calibration data set. The respective equations and r^2 values are also presented in the table ($n = 72$).

Quality parameter	Waveband	Equation	r^2
Simple ratio of reflectance			
NDF (%)	765, 955	NDF = 96.26 − 26.39(R765/R955)	0.187
ADF (%)	725, 1335	ANF = 43.55 − 14.73(R725/R1335)	0.245
CP (%)	605, 515	CP = 38.49 − 23.27(R605/R515)	0.616
Biomass (Mg ha^{-1})	915, 975	Biomass = −25.48 + 28.03(R915/R975)	0.443
CPA (kg ha^{-1})	875, 725	CPA = −558.39 + 492.27(R875/R725)	0.634
First derivatives of reflectance			
NDF (%)	995	NDF = 76.18 − 7223.2(FDR995)	0.259
ADF (%)	645	ANF = 36.08 + 7928.7(FDR645)	0.238
CP (%)	545	CP = 14.68 − 26383(FDR545)	0.582
Biomass (Mg ha^{-1})	935	Biomass = 2.65 − 3442.56(FDR935)	0.487
CPA (kg ha^{-1})	755	CPA = 24.06 + 264930(FDR755)	0.680

Table 3. Five wavebands (±5 nm) selected from stepwise regression for determining relationships between canopy reflectance (*R*) or first derivatives of the reflectance (FDR) and forage neutral detergent fiber (NDF), acid detergent fiber (ADF), crude protein (CP) concentrations, aboveground biomass (BM), and CP availability (CPA) on the basis of calibration data set. The respective equations and their r^2 values are also presented in the table ($n = 72$).

Quality parameter	Selected waveband (bands 1, 2, 3, 4, 5)	Equation	r^2
Reflectance			
NDF (%)	715, 765, 775, 955, 1105	NDF = 74.4 + 40.4(R1) − 836.1(R2) + 752.1(R3) + 236.7(R4) − 177.3(R5)	0.302
ADF (%)	435, 455, 645, 1455, 1485	ADF = 36.9 − 1258.4(R1) + 1119.2(R2) − 183.9(R3) + 477.5(R4) − 369.4(R5)	0.488
CP (%)	425, 505, 605, 1695, 1995	CP = 6.7 + 193.5(R1) + 366.6(R2) − 376.1(R3) + 35.2(R4) − 30.8(R5)	0.732
BM (Mg ha^{-1})	895, 1175, 1975, 2025, 2235	BM = 5.97 + 31.89(R1) − 35.41(R2) + 88.78(R3) − 52.76(R4) − 32.63(R5)	0.638
CPA(kg ha^{-1})	535, 725, 875, 2075, 2225	CPA = 52.7 + 11489(R1) − 8742.2(R2) + 3894.3(R3) + 2987.8(R4) −3801.7(R5)	0.738
First derivative of reflectance			
NDF (%)	485, 545, 765, 995, 2245	NDF = 69.8 − 31103(FDR1) + 35992(FDR2) + 5981(FDR3) − 9819(FDR4) − 1070(FDR5)	0.496
ADF (%)	495, 1175, 1185, 1265, 1475	ADF = 34.3 − 6262.5(FDR1) − 5427.4(FDR2) − 6352.5(FDR3) + 25492(FDR4) − 3750.3(FDR5)	0.473
CP (%)	405, 545, 755, 1225, 1495	CP = 10.41 + 9972.4(FDR1) − 27017(FDR2) + 1058.2(FDR3) − 7208.5(FDR4) + 5194.1(FDR5)	0.739
BM (Mg ha^{-1})	935, 1015, 1045, 1535, 2165	BM = 4.95 − 4295.16(FDR1) − 2883.74(FDR2) + 7140.88(FDR3) − 4660.26(FDR4) + 655.30(DFR5)	0.668
CPA(kg ha^{-1})	745, 755, 1015, 2155, 2235	CPA = 142.8 + 86593(FDR1) + 209944(FDR2) − 415756(FDR3) − 70503(FDR4) + 30588(FDR5)	0.755

tance ratio and first derivatives of reflectance in Table 2. These forage variables were also predicted by the models of the stepwise regression in Table 3 on the basis of the reflectance data. The predicted values were further compared with corresponding laboratory measured values (Fig. 3). Scatter plots comparing forage NDF predicted by the respective equations with measured values indicated that although the RMSE between measured and predicted NDF were small (2.7–3.2%), the r^2 values between the predicted and measured NDF were low ($0.26 \leq r^2 \leq 0.32$) for all the four algorithms ($n = 72$). Additionally, NDF was overestimated when it was <70% and underestimated when it was >70%.

Similar to the prediction of forage NDF, the r^2 of predicted and measured ADF were low ($0.28 \leq r^2 \leq 0.35$) and ADF was overestimated when it was <35% and underestimated when it was >35%. Stepwise regression models did not improve prediction efficiency of either NDF or ADF although stepwise regression equations of NDF and ADF with reflectances and first derivatives of reflectance in calibration data set had slightly greater r^2 (Table 3) than the simple linear models in Table 2. Low correlation of the canopy reflectance ratios or derivatives of reflectance with NDF and ADF of bermudagrass pastures and poor prediction of the NDF and ADF in the present study were probably associated with small ranges of variance in these two quality variables (see Table 1). These results also indicated that it might be more difficult to accurately predict forage NDF and ADF using canopy reflectance measurements in just one to five narrow wavebands, as compared with CP concentration.

In the present study, both the reflectance ratios and the first derivatives of reflectance could be used to adequately predict forage CP concentration, biomass production, and CP availability with $r^2 = 0.58$ to 0.81, $P <$ 0.0001 (Fig. 3a and 3b). These three forage variables exhibited a wide range in values (Table 1) and the RMSE between predicted and measured values were 1.47 to 1.55% for CP concentration, 1.16 to 1.21 Mg ha^{-1} for biomass, and 87.5 to 97.8 kg ha^{-1} for CP availability in all the models of the reflectance ratio, first derivatives of reflectance, and their stepwise regression equations. Furthermore, assessment of scatter plots of measured NDF, ADF, CP, biomass, and CP availability versus predicted values using the equations in Table 3 suggested that the multi-variable equations did not improve prediction accuracy of any measured forage quality variable (Fig. 3c and 3d), as compared with the simple models of reflectance ratio or first derivatives of reflectance. This is probably associated with existence of multicolinearity in stepwise regression.

Evidence has indicated that leaf N concentration can be estimated from leaf level reflectance measurements, especially the reflectance ratios or the first derivatives of reflectance in given wavebands (Carter and Spiering, 2002; Lamb et al., 2002; Zhao et al., 2005a, 2005b). Our results suggest that simple reflectance ratios or the first derivatives of reflectance from canopy level measurements could be used to predict CP concentration and CP availability of field standing bermudagrass pastures.

CONCLUSIONS

Crude protein concentration, biomass production, and CP availability of bermudagrass pastures closely correlated with canopy reflectance ratios of R_{605}/R_{515}, R_{915}/R_{975}, and R_{865}/R_{725}, respectively. These three forage variables were also correlated with the first derivatives of reflectance in wavebands centered at 545, 935, and 755 nm, respectively. The NDF and ADF of bermudagrass pastures had lower correlation with either the reflectance ratios or the first derivatives of reflectance compared with other forage quality variables measured. All the relationships between measured forage biomass and nutritive values and the reflectance ratios or the first derivatives of reflectance could be expressed by simple linear functions. The results of validating the developed linear models indicated that although the relationships

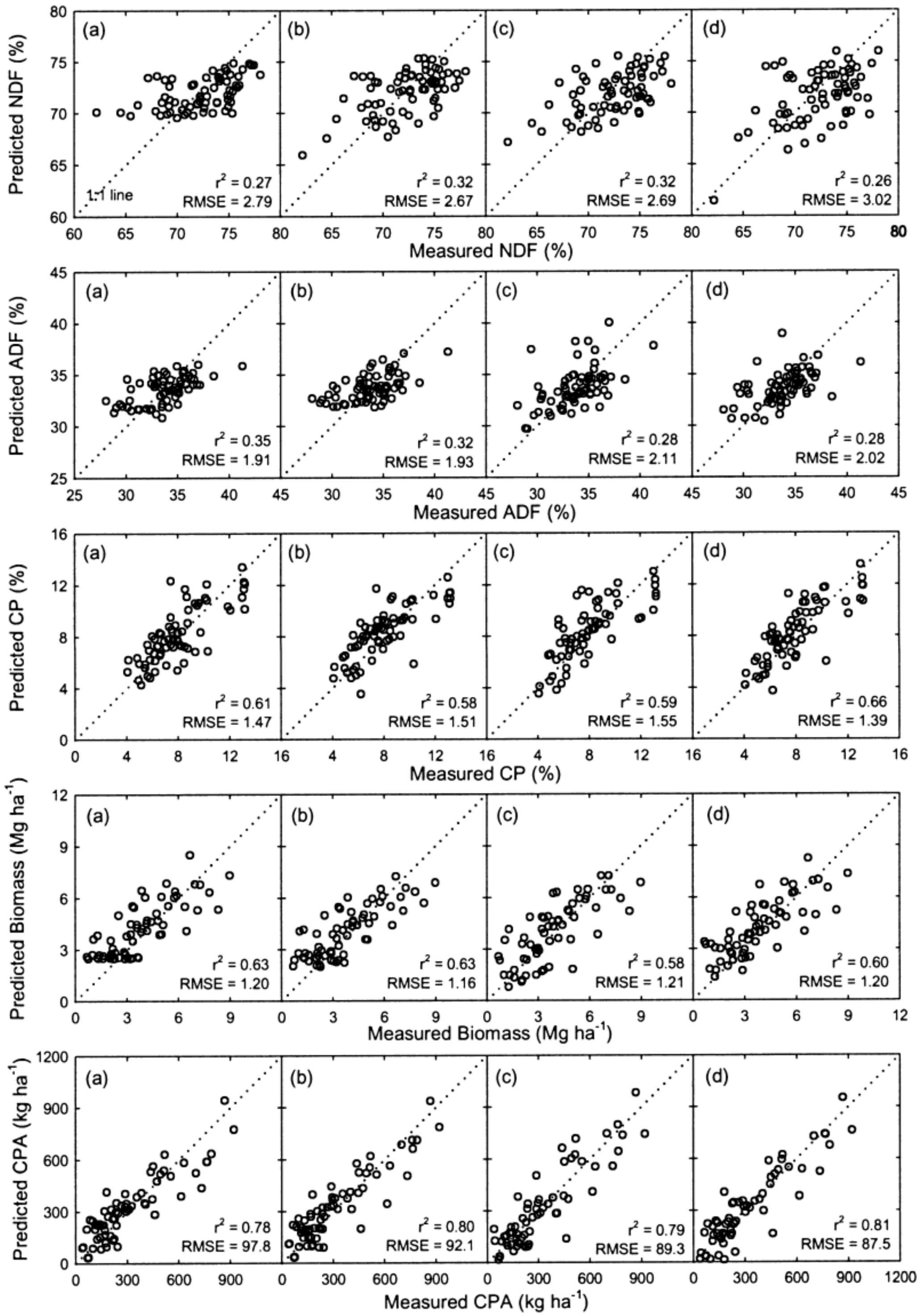

Fig. 3. Comparison of laboratory measured forage neutral detergent fiber (NDF), acid detergent fiber (ADF), crude protein (CP) concentrations, aboveground biomass, and CP availability (CPA) in the test data set with their predicted values based on the equations developed with (a) reflectance ratios, (b) first derivatives of reflectance, (c) stepwise regression of reflectance, and (d) stepwise regression of the first derivative of reflectance in Tables 2 and 3 (n = 72). Dotted line represents predicted = measured values.

of forage NDF and ADF with pasture canopy reflectance were poor, the CP concentration, biomass production and CP availability of bermudagrass could be adequately predicted throughout the growing seasons using two-waveband reflectance ratios or the first derivatives of reflectance. Therefore, remote sensing of canopy reflectance in certain narrow wavebands can be used for real-time and nondestructive assessment of forage productivity and crude protein concentration in bermudagrass pastures.

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REFERENCES

Blackmer, T.M., J.S. Schepers, G.E. Varvel, and E.A. Walter-Shea. 1996. Nitrogen deficiency detection using reflected shortwave radiation from irrigated corn canopies. Agron. J. 88:1–5.

Campbell, J.B. 1996. Introduction of remote sensing. 2nd ed. The Guilford Press, London.

Carter, G.A., and L. Estep. 2002. General spectral characteristics of leaf reflectance responses to plant stress and their manifestation at the landscape scale. p. 271–293. *In* R.S. Muttiah (ed.) From laboratory spectroscopy to remotely sensed spectra of terrestrial ecosystems. Kluwer Academic Publishers. The Netherlands.

Carter, G.A., and B.A. Spiering. 2002. Optical properties of intact leaves for estimating chlorophyll concentration. J. Environ. Qual. 31:1424–1432.

Chappelle, E.W., M.S. Kim, and J.E. McMurtrey, III. 1992. Ratio analysis of reflectance spectra (RARS): An algorithm for the remote estimation of the concentrations of chlorophyll *a*, and chlorophyll *b*, and carotenoids in soybean leaves. Remote Sens. Environ. 39:239–247.

Curran, P.J., J.L. Dungan, B.A. Macler, S.E. Plummer, and D.L. Peterson. 1992. Reflectance Spectroscopy of fresh whole leaves for the estimation of chemical concentration. Remote Sens. Environ. 39:153–166.

Daughtry, C.H.T., C.L. Walthall, M.S. Kim, E.B. de Colstoun, and J.E. McMurtrey, III. 2000. Estimating corn leaf chlorophyll concentration from leaf and canopy reflectance. Remote Sens. Environ. 74: 229–239.

Everitt, J.H., A.J. Richardson, and H.W. Gausman. 1985. Leaf reflectance-nitrogen-chlorophyll relations in buffelgrass. Photogramm. Eng. Remote Sens. 51:463–466.

Filella, I., L. Serrano, J. Serra, and J. Peñuelas. 1995. Evaluating wheat nitrogen status with canopy reflectance indices and discriminant analysis. Crop Sci. 35:1400–1405.

Gausman, H.W. 1982. Visible light reflectance, transmittance, and absorption of differently pigmented cotton leaves. Remote Sens. Environ. 13:233–238.

Hruschka, W.R. 1987. Data analysis: Wavelength selection methods. p. 35–55. *In* P. Williams and K.H. Norris (ed.) Near-infrared technology in the agriculture and food institutes. American Association of Cereal Chemists, St. Paul, MN.

Kellems, R.O., and D.C. Church. 1998. Roughages. p. 59–84. *In* R.O. Kellems and D.C. Church (ed.) Livestock feeds and feeding. 4th ed., Prentice Hall, Inc., Englewood Cliffs, NJ.

Kokaly, R.F. 2001. Investigating a physical basis for spectroscopic estimates of leaf nitrogen concentration. Remote Sens. Environ. 75: 153–161.

Lamb, D.W., M. Steyn-Ross, P. Schaare, M.M. Hanna, W. Silvester, and A. Steyn-Coss. 2002. Estimating leaf nitrogen concentration in ryegrass (*Lolium* spp.) pasture using the chlorophyll red-edge: Theoretical modeling and experimental observations. Int. J. Remote Sens. 23:3619–3648.

Ma, B.L., M.J. Morrison, and L.M. Dwyer. 1996. Canopy light reflectance and field greenness to assess nitrogen fertilization and yield of maize. Agron. J. 88:915–920.

Marten, G.C., J.S. Shenk, and F.E. Barton, II. 1989. Near infrared reflectance spectroscopy (NIRS): Analysis of forage quality. USDA-ARS Handbook 643, U.S. Gov. Print. Office, Washington, DC.

Norris, K.H., R.F. Barnes, J.E. Moore, and J.S. Shenk. 1976. Predicting forage quality by infrared reflectance spectroscopy. J. Anim. Sci. 43: 889–897.

Pearson, C.D., and R.L. Ison. 1987. Agronomy of grassland systems. Cambridge Univ. Press, Cambridge, England.

Peñuelas, J., and I. Filella. 1998. Visible and near-infrared reflectance techniques for diagnosing plant physiological status. Trends Plant Sci. 3:151–156.

Peñuelas, J., and Y. Inoue. 2000. Reflectance assessment of canopy CO_2 uptake. Int. J. Remote Sens. 21:3353–3356.

Plant, R.E., D.S. Munk, B.R. Roberts, R.L. Vargas, D.W. Rains, R.L. Travis, and R.B. Hutmacher. 2000. Relationships between remotely sensed reflectance data and cotton growth and yield. Trans. ASAE 43:535–546.

Read, J.J., L. Tarpley, J.M. McKinion, and K.R. Reddy. 2002. Narrow-waveband reflectance ratios for remote estimation of nitrogen status in cotton. J. Environ. Qual. 31:1442–1452.

Reddy, K.R., D. Zhao, V.G. Kakani, J.J. Read, and S. Koti. 2003. Estimating cotton growth and development parameters through remote sensing. p. 277–288. *In* W. Gao and D. Shaw (ed.) Proc. SPIE. Vol. 5153. Ecosystems dynamics, agricultural remote sensing and modeling, and site-specific agriculture. SPIE, Bellingham, WA.

Richardson, A.J., J.H. Everitt, and H.W. Gausman. 1983. Radiometric estimation of biomass and nitrogen content of Alicia grass. Remote Sens. Environ. 13:179–184.

SAS Institute Inc. 1997. SAS User Guide: Statistics. SAS Institute Inc., Cary, NC.

Shenk, J.S., and M.O. Westerhaus. 1994. The application of near infrared reflectance spectroscopy (NIRS) to forage analysis. p. 406–449. *In* G.C. Fahey Jr. et al. (ed.) Forage quality, evaluation, and utilization. ASA-CSSA-SSSA, Madison, WI.

Starks, P.J., S.W. Coleman, and W.A. Phillips. 2004. Determination of forage chemical composition using remote sensing. J. Range Manage. 57:635–640.

Starks, P.J., D. Zhao, W.A. Phillips, M.A. Brown, and S.W. Coleman. 2005. Productivity and forage quality of warm season grass pastures in relation to canopy reflectance in ASTER wavebands. Proc. 20th Biennial Workshop on Aerial Photography, Videography, and High Resolution Digital Imagery for Resource Assessment. 4–6 Oct., 2005. Weslaco, TX.

Taliaferro, C.M., G.L. Williams, J. Enis, and S.W. Coleman. 1995. Performance of forage bermudagrass varieties in Oklahoma, 1992–1994. Production Technology-Crops. Cooperative Extension Service, Oklahoma State University, PT-95–11.

Taliaferro, C.M., G.L. Williams, T.G. Pickard, D.W. Hooper, S.W. Coleman, and W.A. Phillips. 2000. Performance of forage bermudagrass varieties in Oklahoma, 1995–1999. Production Technology-Crops. Cooperative Extension Service, Oklahoma State University, PT-2000–8.

Voullot, M.O., P. Huet, and P. Boissard. 1998. Early detection of N deficiency in a wheat crop using physiological and radiometric methods. Agronomie 18:117–130.

Wang, R.C., K. Wang, and Z.Q. Shen. 1998. Feasibility of field evaluation of rice nitrogen status from reflectance spectra of canopy. Pedosphere 8:121–126.

Zhao, D., K.R. Reddy, V.G. Kakani, J.J. Read, and S. Koti. 2005a. Selection of optimum reflectance ratios for estimating leaf nitrogen and chlorophyll concentrations of field-grown cotton. Agron. J. 97: 89–98.

Zhao, D., K.R. Reddy, V.G. Kakani, and V.R. Reddy. 2005b. Nitrogen deficiency effects on plant growth, leaf photosynthesis, and hyperspectral reflectance properties of sorghum. Eur. J. Agron. 22: 391–403.